Time-Domain Astronomy

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26th March 2026

Papers for presentations on Pulsars

Devash: Milliseconds Pulsars, Backer 1984
(https://ui.adsabs.harvard.edu/abs/1984JApA....5..187B/abstract)

Pinki: RADIO PULSARS — AN OBSERVER'S PERSPECTIVE, Lorimer 1999
(https://arxiv.org/pdf/astro-ph/9911324)

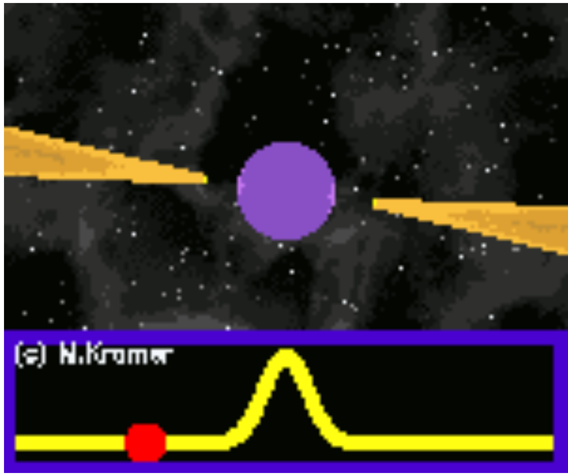
Saurabh: DISCOVERY OF A PULSAR IN A BINARY SYSTEM, Hulse & Taylor 1975
(https://ui.adsabs.harvard.edu/abs/1975ApJ...195L..51H/abstract)

Yashraj: Pulsar timing and its applications , Manchester 2018
(https://arxiv.org/abs/1801.04318)

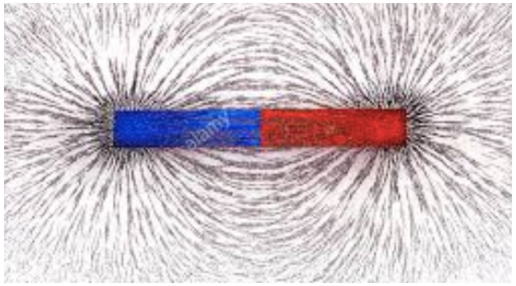
Esha: Archibald et al. 2009, Science, 324, 1411
"A Radio Pulsar/X-ray Binary Link"
(https://arxiv.org/pdf/0905.3397)

Zuned: FAST Discovery of Eight Isolated Millisecond Pulsars in NGC 6517, Yin 2024 (https://arxiv.org/abs/2405.18228)

Pulsars : Rapidly rotating strongly magnetized neutron stars



Neutron stars : Highly magnetized laboratories in sky



Magnetic field of refrigerator = 100 G

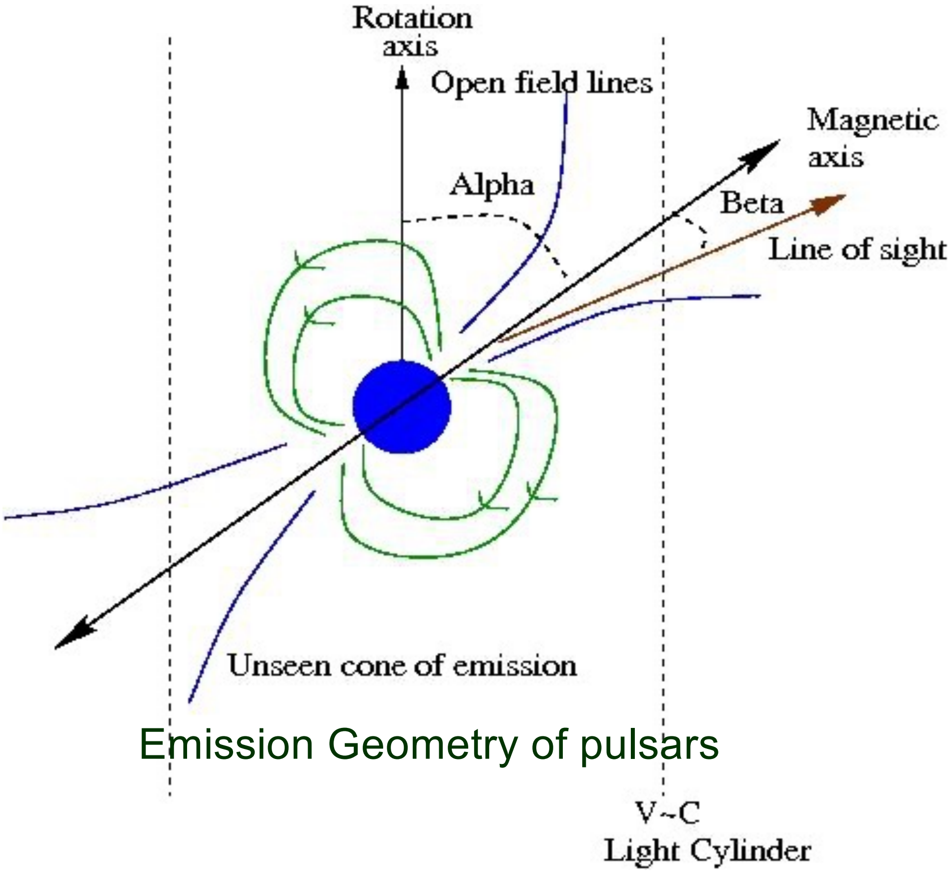
Magnetic filed of typical bar magnet = 10-100 G

Magnetic field of Earth = 0.5 G

Magnetic field of Sun = 1 G

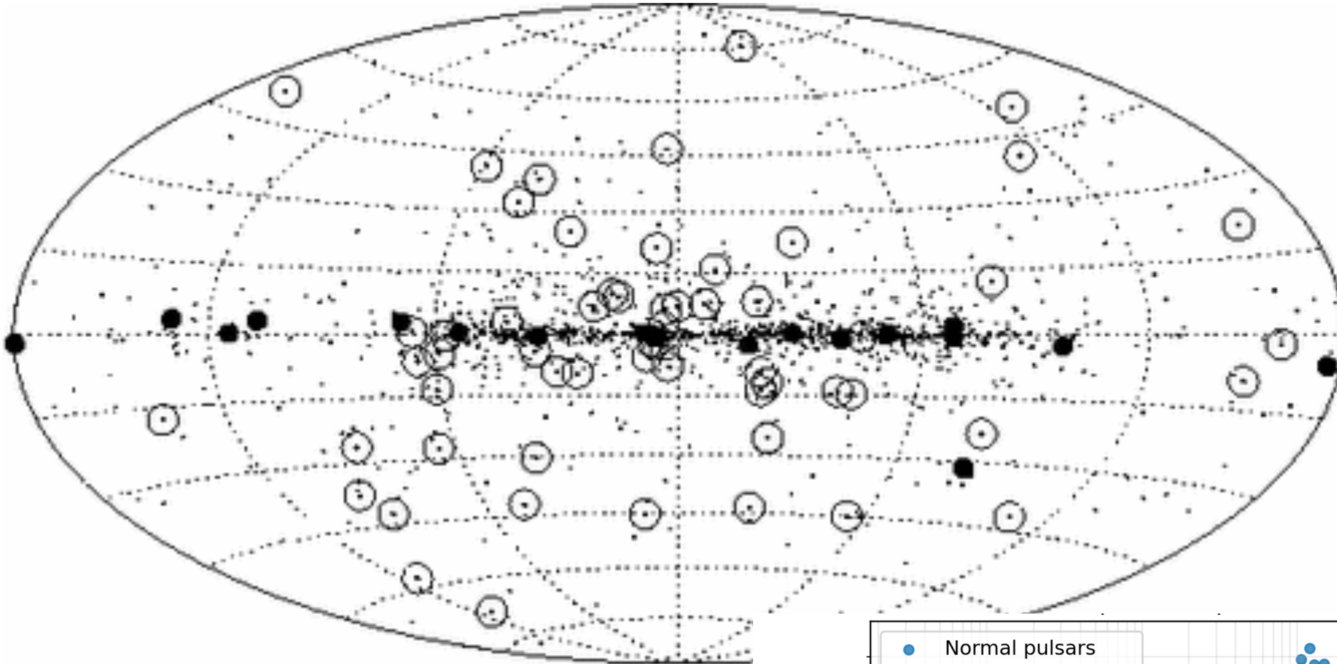
Strongest magnet in Earth = 25,0000 G

Magnetic field of Neutron star 10^8 to 10^{15} G –100 billion times Earth

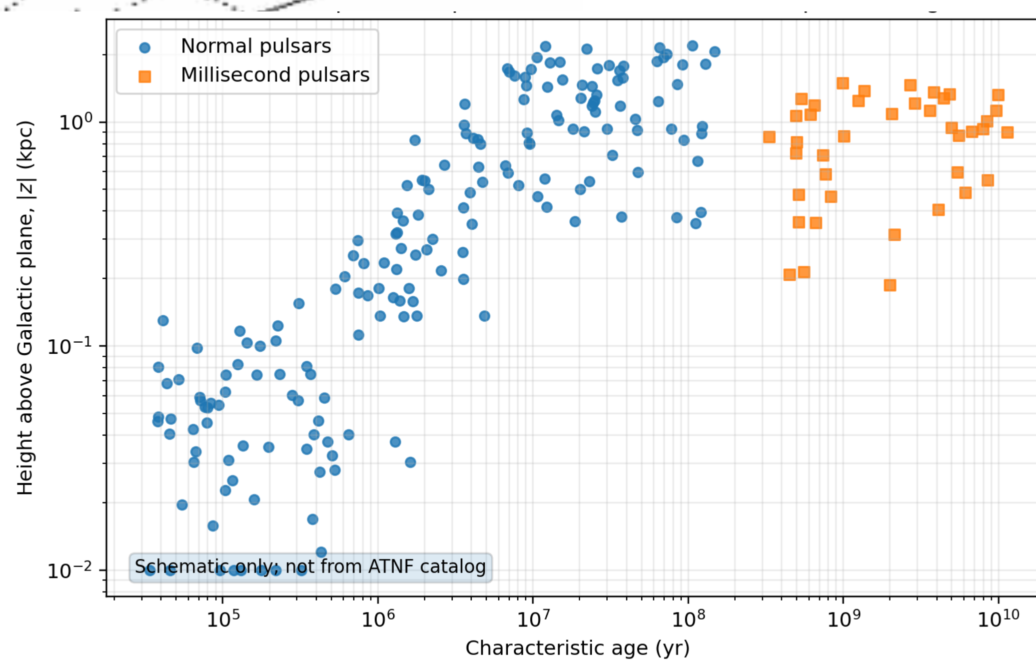


Emission Geometry of pulsars

And what we can learn from the pulsar sky coordinates?



Taken from "Handbook of Pul



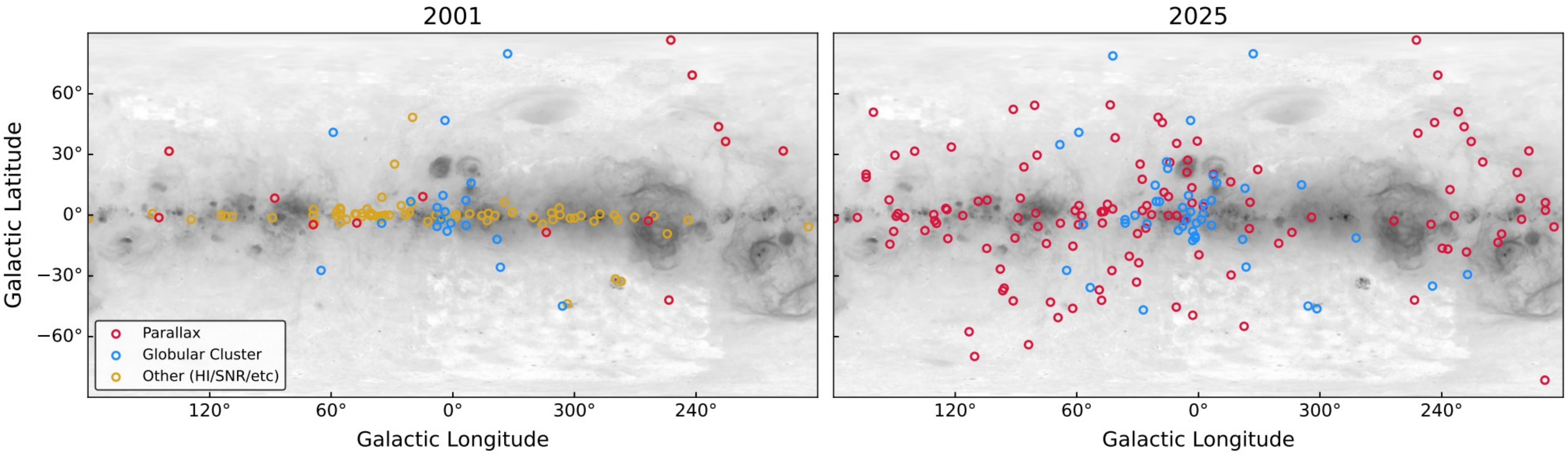
Most of the pulsars are sitting in the Galactic disk. All the supernova remnant pulsars (i.e. very young pulsars) are in the galactic plane. But the binary pulsars (remember, that most of them are millisecond pulsars) are distributed more unifrormly. Why?

Luckily we know that (at least to some extent). There is a model of free electron distribution in our galaxy - by Taylor & Cordes (1993).

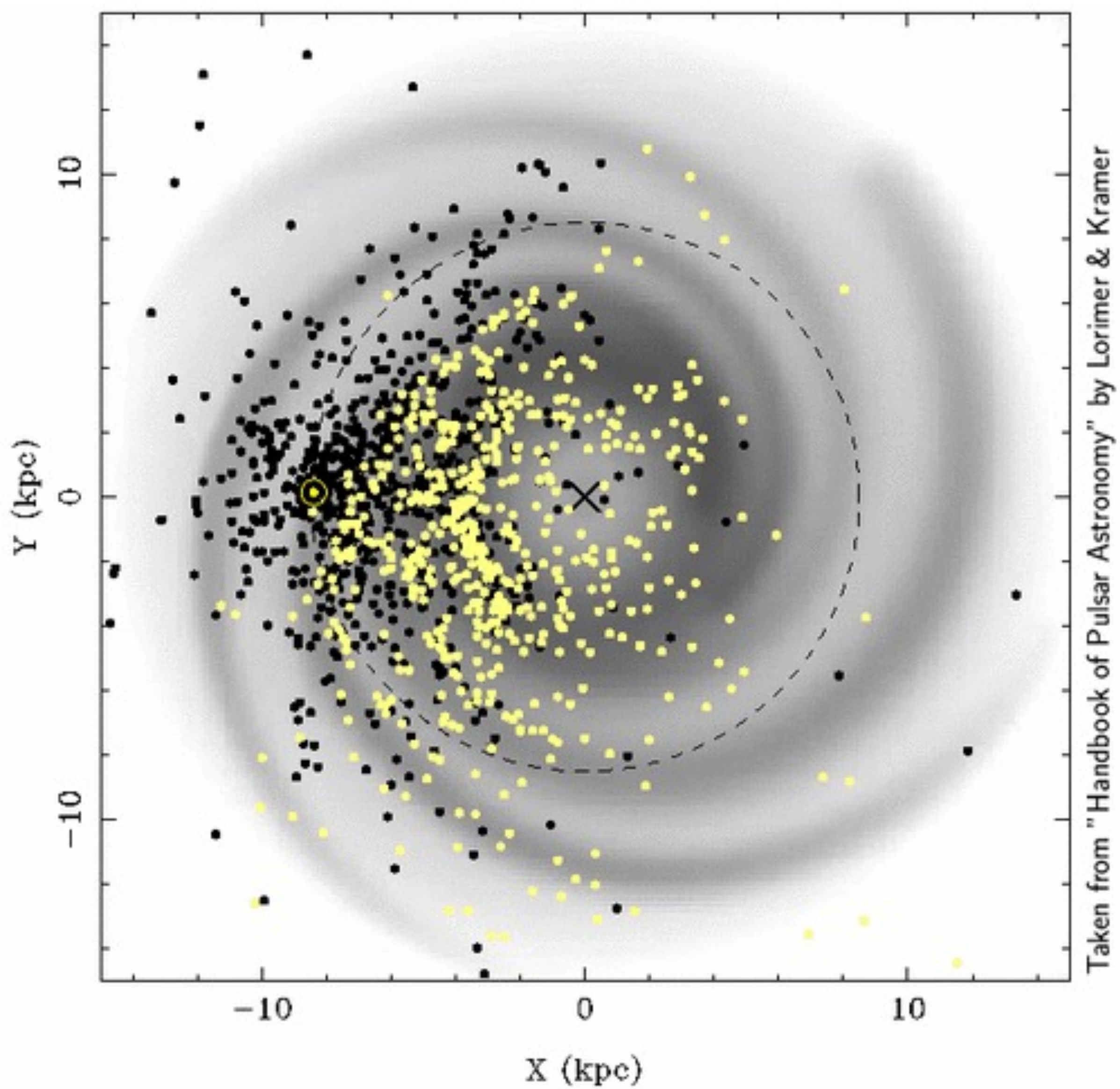
It gives us the means to transform the DM value to the pulsar distance.

In comparison to the other methods of ascertaining the pulsar distance it is not a very accurate method (up to 50% errors in value)

Using these values we can place the pulsars we see in the Milky Way spiral structure.



The Galactic distribution of pulsars

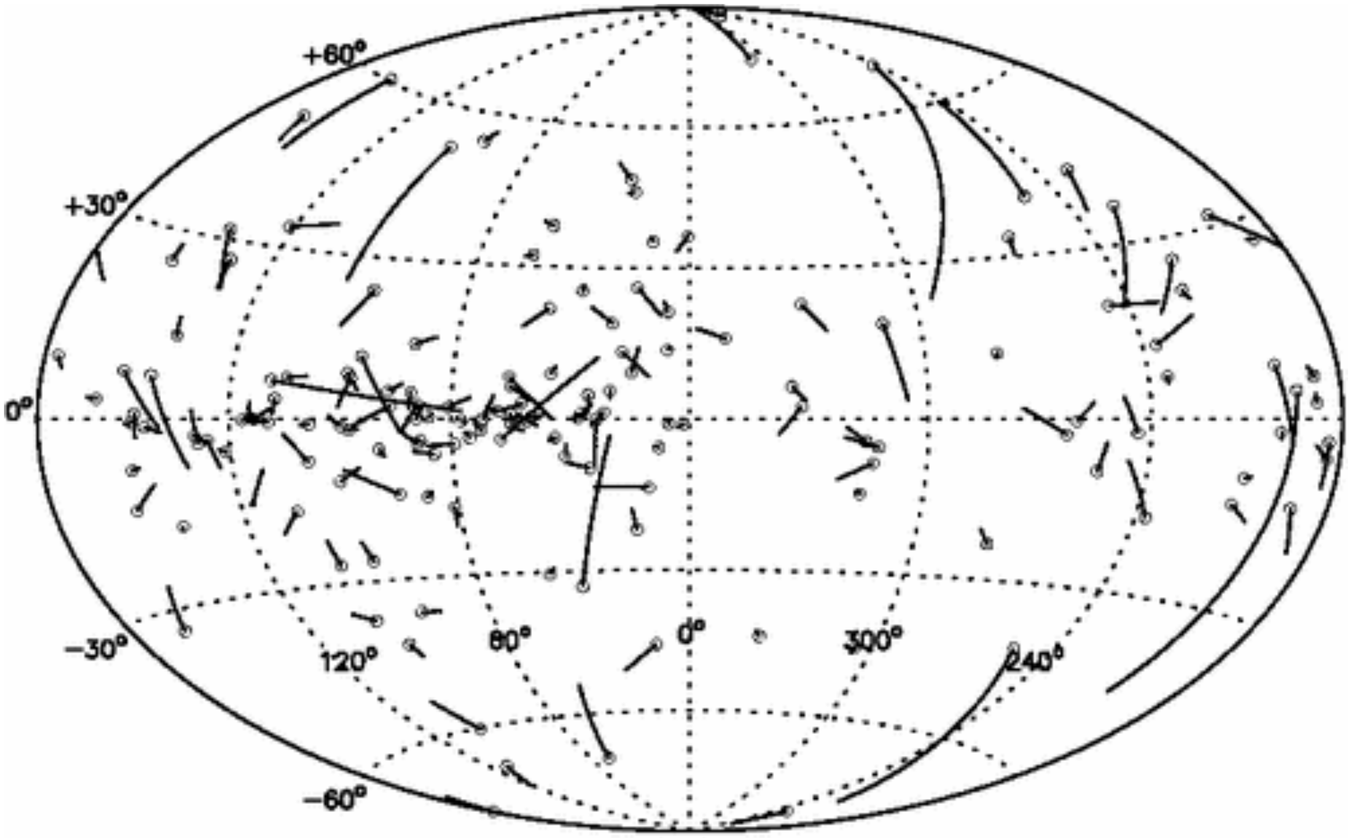


Dark points are the pulsars discovered by old surveys (mainly at low frequencies).

Bright points - pulsars discovered in the Parkes Multibeam Survey at higher frequencies (1.4 GHz and more).

The grayscale picture of our Galaxy is actually the free electron density in the galactic plane.

In many cases we know not only where the pulsars are, but also - how they move:



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

The circles show the current pulsar positions, solid lines represent their movements over the last million years.

Pulsars as astrophysics ”tools”.

Due to their physical properities pusars are (in most cases) VERY stable rotators – one needs an unimaginable force to unhinge it.

The incomming pulses of radiation may be therefore treated as ”ticking” of cosmic clocks.

This way we can treat pulsars as naturally created probes of specific conditions in which they exist – i.e. strong gravitational fields.

This also allows to investigate their dynamics – especially the movement caused by external forces. This includes binary systems, and globular clusters dynamics.

So, how to measure pulsar period?

Pulsar Timing – a cryptic name for a very simple procedure:

- how to measure how long is a second on your watch?

- prediction and observation of pulse arrival time (TOA)

- pulsar timing model – a collection of the important physical parameters, describing its rotation, movement etc.

- implifications: what causes the pulses to appear later/sooner than we expected?

What to remember when you want to predict pulse arrival time?

Universe is in a constant motion.

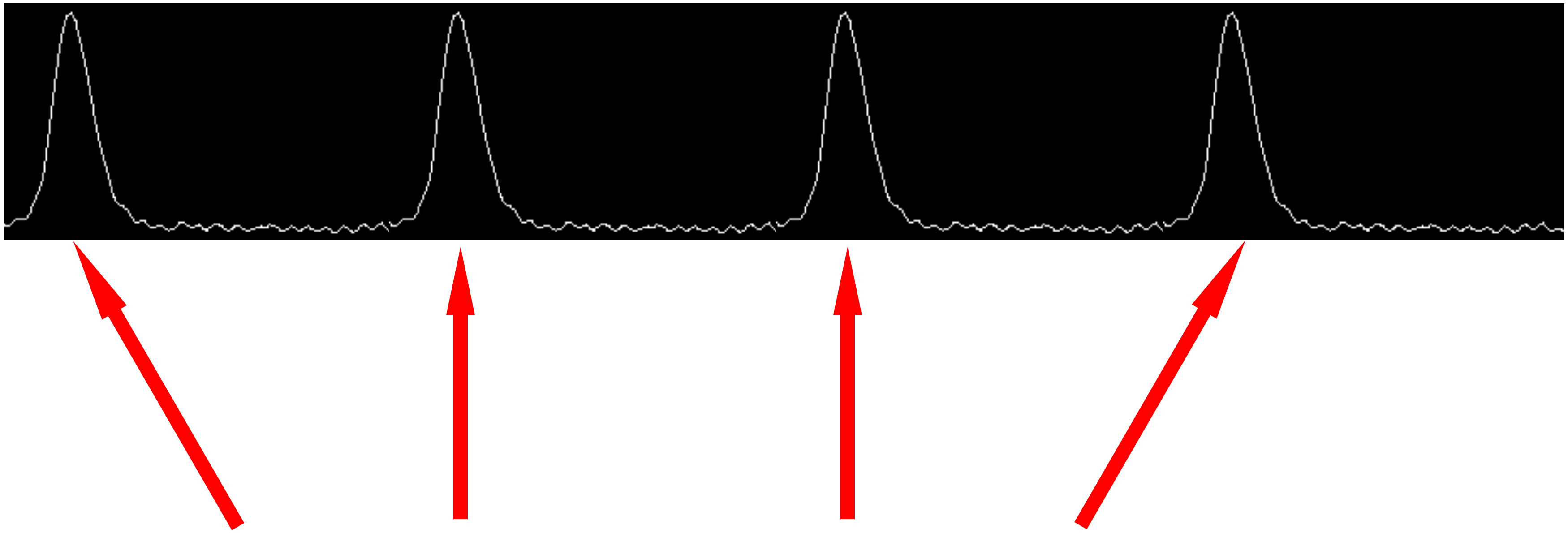
We observe pulsars from a point on the surface of Earth but this point is moving in a very complicated way.

One has to take into accout a number of effects affecting our movement in the Universe: gravitational interactions in our solar system, and Earth's rotation, which in reality is not steady – it's axis is changing, and the rotation is slowing down.

So, how the timing actually works?

Let's suppose, that you've done some timing observations for one pulsar, over three years, taking some 250 TOA measurements.

Time of Arrival (TOA) is the moment in time, when the pulsar reaches some arbitrary decided phase (usually close to the pulse maximum).



Times of Arrival (TOA's) for consecutive pulses.

Then it is necessary to aply all prevoiusly mentioned corrections to your TOA's (basically subtract your observatory position and movement). This is done by recalculating the TOAs to the solar system barycenter:

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D / f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

Roemer delay

Shapiro delay

Einstein delay

t_{topo} – topocentric arrival time
t_{corr} – clock corrections due to the Earth rotation unstabilities
*ΔD = D * DM*, where *D* – disspersion measure constant, and *DM* - a disspersion measure of the pulsar

t_{corr} – is the clock correction, i.e. the time difference between the observatory time and the real Earth time.

First, you have to apply the correction to match your observatory clock to the UTC time standard (e.g. The GPS time).

Due to the earth rotation slow-down the UTC is not continous time, there were some ”leap seconds” added to it over time the continous timescale is called TAI (International Atomic Time).

There are also the corrections due to the instabilities in the Earth rotation – the movement of the North Pole, the changes of rotational speed due to the ocean tides.

The UT1 is a non-uniform timescale which tracks these changes. The problem with UT1 is, that this time is known post-factum, i.e. it takes 2-3 weeks to calculate what UT1 time was at any given UTC moment.

The difference between the TAI and UT1 (left) and the length of day excess to the 84600 seconds, shown in milliseconds (right).

Figure O-3: Universal time, 1994-1998. 5-d values of Table O-4.

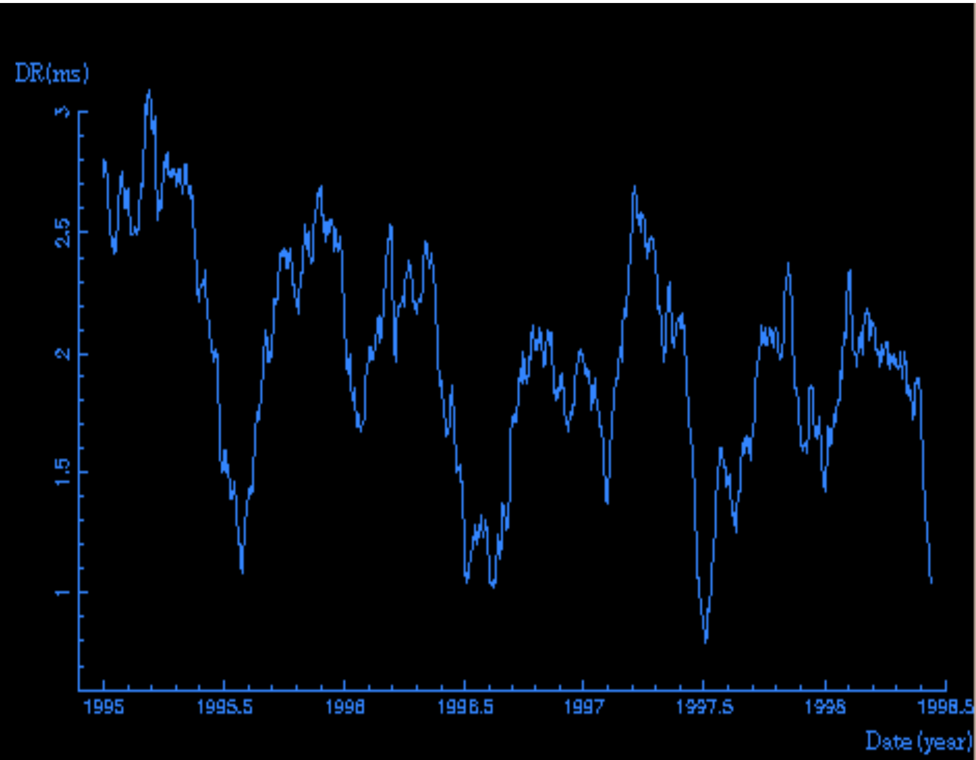


Figure O-4: Excess to 86400s of the duration of the days, combined GPS solution, 1995-1998.

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

The Roemer Delay is the classical light travel delay between the Solar System barycenter and the centre of the telescope. It can be described as:

$$\Delta_{R\odot} = -\frac{1}{c}\vec{r} \cdot \hat{s} = -\frac{1}{c}(\vec{r}_{\mathrm{SSB}} + \vec{r}_{\mathrm{EO}}) \cdot \hat{s}$$

It can reach 500 seconds (the time that the light needs to travel from SSB (or the Sun) to Earth. The telescope position vector is usualy split into two: the vector from the SBB to the geocenter, and the geocentric vector of the telescope.

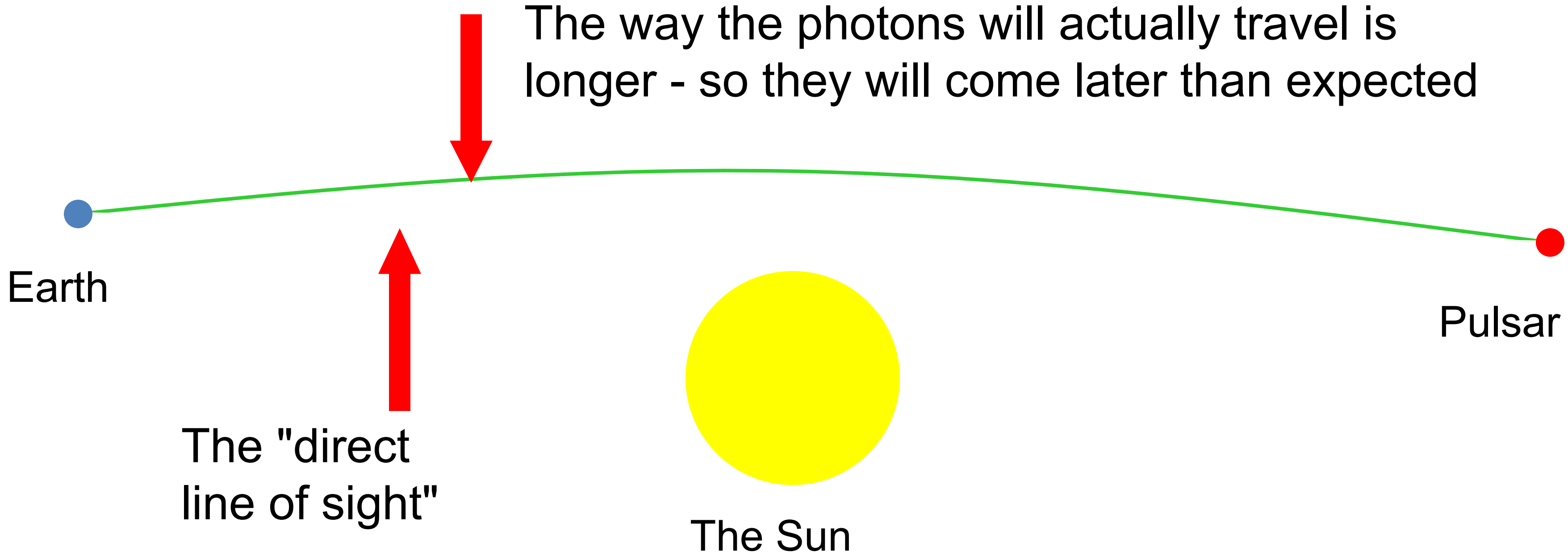
To properly calculate the $\vec{r}_{SBB}$ vector one needs very precise solar system ephemeris - usually the JPL DE200 or DE405 ephemeris, that take into account all masses in the solar system up to the few of the largest asteroids.

Calculation of the $\vec{r}_{EO}$ vector requires very precise knowledge about your telescope location on the surface of the Earth, and - again - all the position corrections due to the North Pole movement, and of course all the other clock corrections (one needs to know the vector at the exact time of observations).

Of course you need also to know very precissely the unit pulsar vector $\vec{s}$ - so already at this stage you need to know the exact pulsar position.

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

The Shapiro Delay is the time correction due to the curvature of space-time, caused by large masses. In our solar system the masses we have to take into account are the Sun and sometimes Jupiter.



Shapiro delay may be expressed as:

$$\Delta_{S\odot} = -2\sum_i \frac{GM_i}{c^3} \ln\left[\frac{\hat{s}\cdot\vec{r}_i^{\mathrm{E}} + r_i^{\mathrm{E}}}{\hat{s}\cdot\vec{r}_i^{\mathrm{P}} + r_i^{\mathrm{P}}}\right]$$

Where the index *i* numbers the celestial bodies of mass M_i taken into account. The superscript *E* denotes the Earth to *i*-th body vector, and *P* denotes the pulsar to *i*-th body vector - both at the time of the closest approach of the photon to that body.

One gets the largest delay for a signal passing the limb of the Sun - approximately 120 μs.

Jupiter can cause the Shapiro delay up to 200 ns.

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

The Einstein Delay is the correction for the time dillatation effect caused by the motion of the Earth (Special Relativity) and gravitational redshift caused by the other bodies in our solar system (General Relativity).

This delay can be calculated from the formula:

$$\frac{d\Delta_{E\odot}}{dt} = \sum_i \frac{GM_i}{c^2 r_i^{\mathrm{E}}} + \frac{v_{\mathrm{E}}^2}{2c^2} - \mathrm{constant}$$

Once you apply all the corrections you have the real barycentric arrival time (barycentric TOA).

At the same time you predict the arrival times - using some basic timing model, i.e pulsar parameters taken from a pulsar catalogue, a paper, or discovery report. You do it for all the observational epochs.

Usually, for solitary pulsars, which show only a simple slow-down (as they are actually producing the radiation on the cost of their rotational energy) you can express the spin frequency as a simple Taylor expansion:

$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2}\ddot{\nu}_0(t - t_0)^2 + \cdots$$

So, to predict the pulse arrival time one needs to know some basic parameters describing pulsar rotation.

Your "timing model" should include pulsar rotational frequency, and it's derivatives. The first derivative is usually called "the slow-down rate". The second derivative is measureble for several of the youngest pulsars only.

The timing model actually includes also the pulsar astrometric parameters: the sky coordinates, proper motions, paralax etc.

This is so because the prediction of the arrival times, and correction of the observed TOAs is done simultaneusly by one software - such as TEMPO[1] package.

[1]TEMPO is maintained and distributed by Princeton University and the Australia Telescope National Facility (see http://www.atnf.csiro.au/research/pulsar/tempo/).

The predicted phase (or pulse number) at any given time *t* may be written as:

$$N = N_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \cdots$$

Where N_0 is the pulse number at the reference epoch t_0.

Usually the predicted barycentric TOAs are different from the observed (and corrected to SSB) TOAs.

The difference between predicted and observed TOAs is called a RESIDUAL.

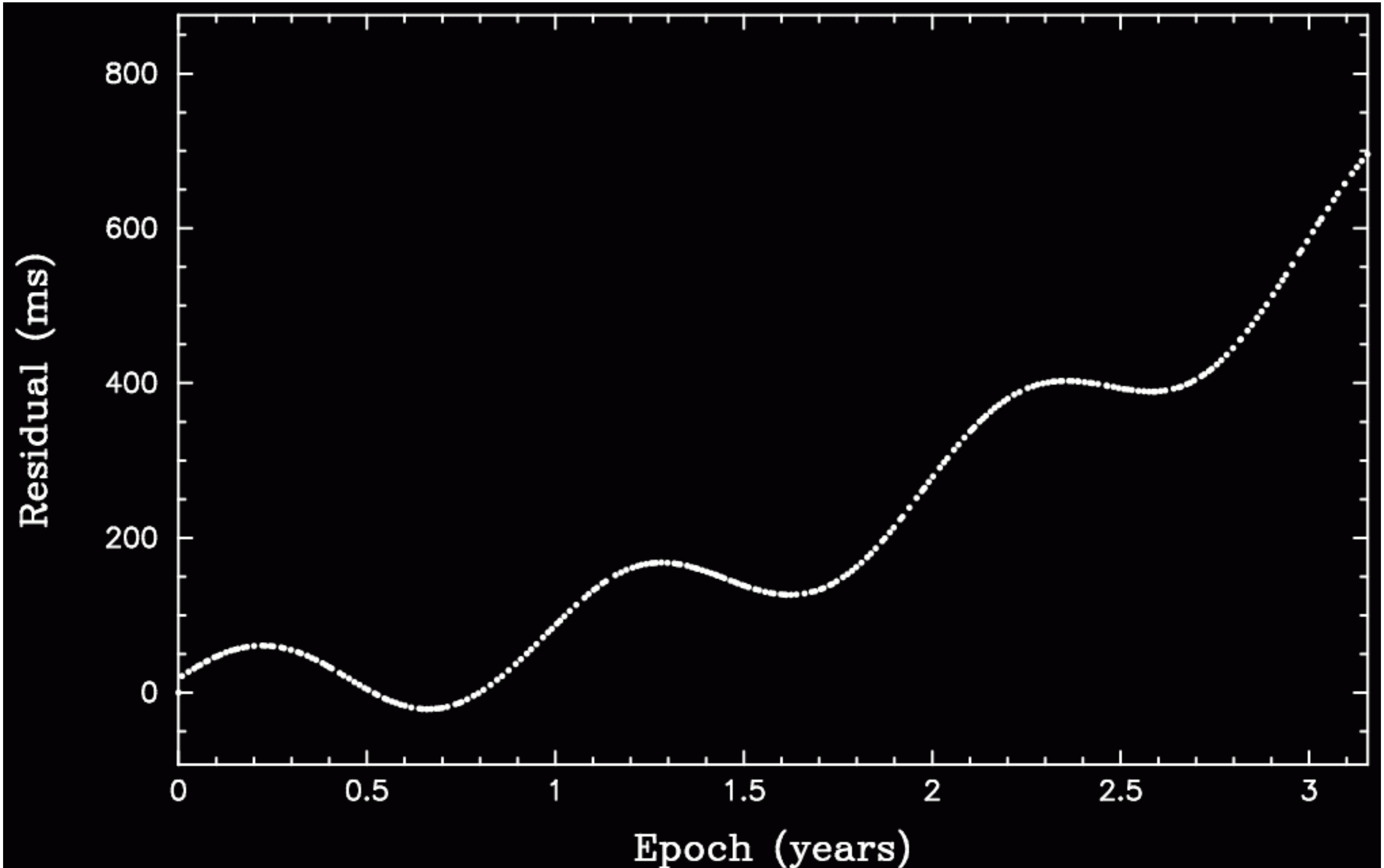
You can't do much with just one residual. To make a proper timing analysis you need more of them, measured at different epochs.

The longer your dataspan is - the better chances you have to undrestand why the residuals are not equal to zero.

The next step is ploting the residuals against the epoch of observation.

From what you see you can conclude what effects cause the deviations. Almost every one of the effects has its own pattern.

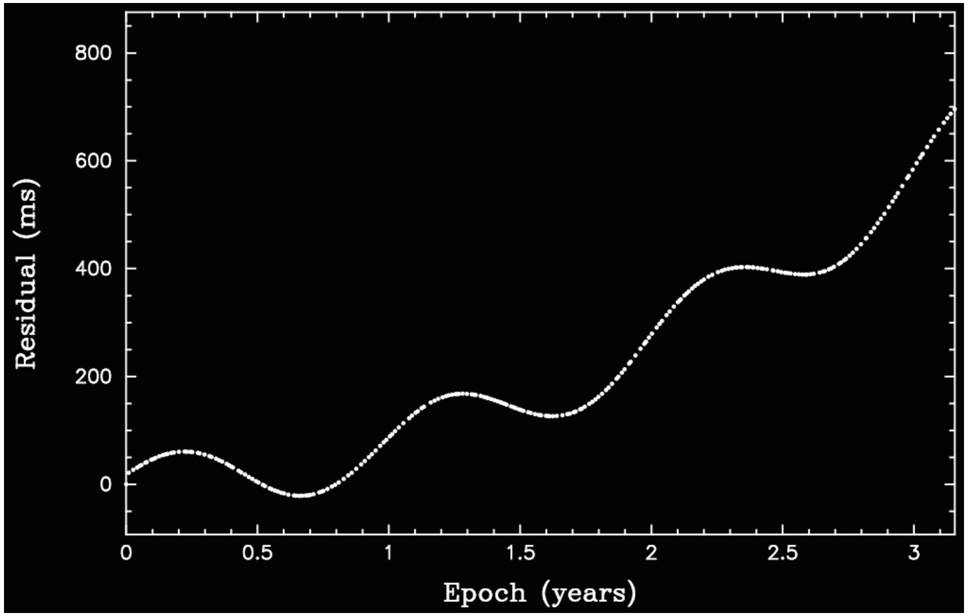
So, what will you usually see when you start to analyse timing data?



The timing procedure allows you to correct/improve on the values of the parameters included in your timing model.

For example - the pulsars are slowing down. The main trend in the example residuals plot may be seen as a parabole.

$$N = N_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \cdots$$



So, it is possible that our prediction was wrong. The cause for that may be the wrong values of ν and ν used in the prediction algorithm.

Two main reasons for that may be, that the pulsar period and/or slow-down rate have really changed, or they were not precise enough to predict the arrival times for our epochs.

Either way the residuals allow us to improve on this values. Usually it is done by least squares method. One can construct a χ^2 function as:

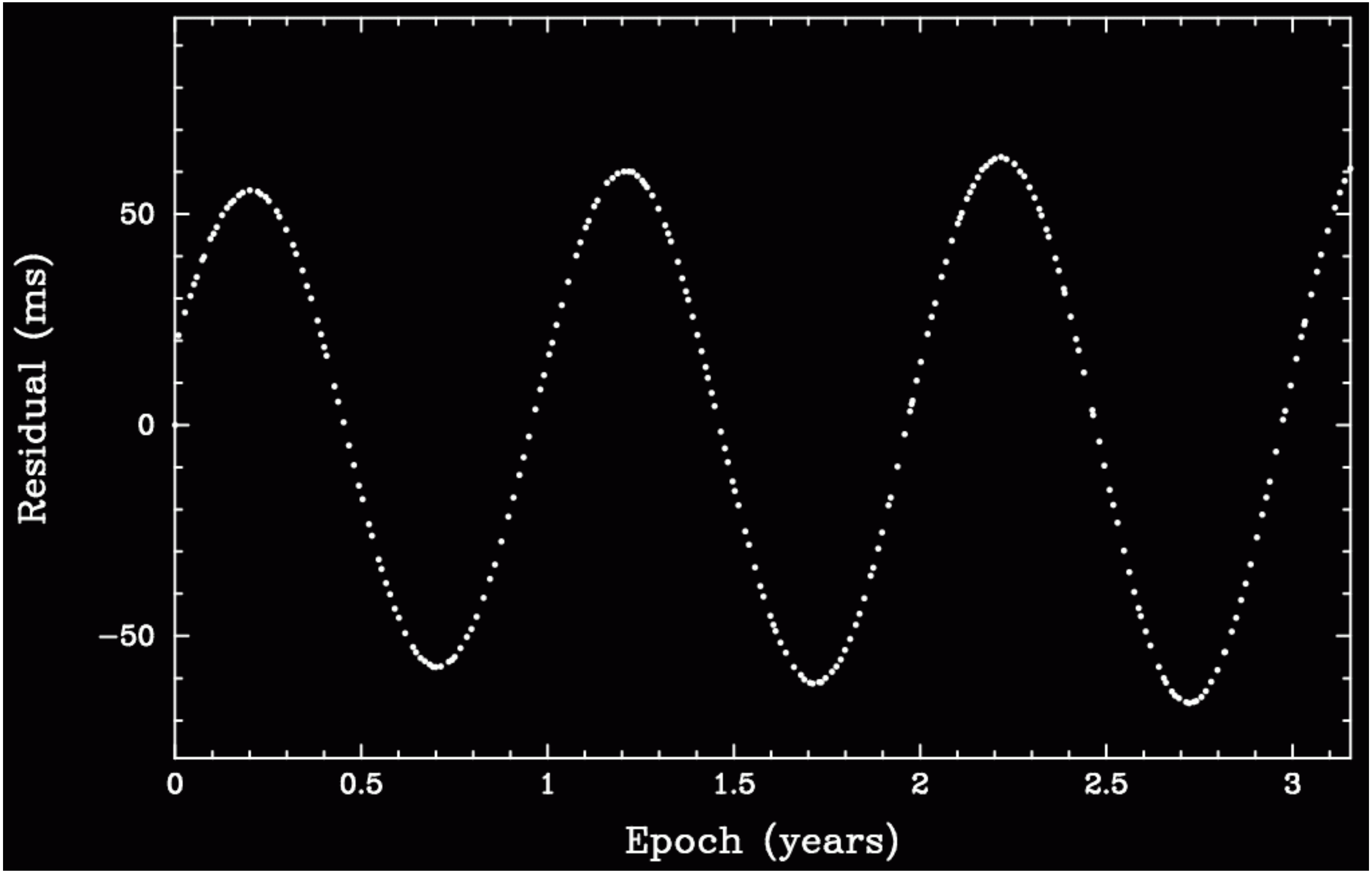
$$\chi^2 = \sum_i \left(\frac{N(t_i) - n_i}{\sigma_i} \right)^2,$$

Where $N(t_i)$ is a predicted pulse number for the observed time t_i, n_i is the closest integer, and σ_i is the TOA uncertainty (actually in units of the pulse period).

By minimizing this function via the changes in ν and ν we can find the proper values of these parameters.
These corrected values are then included in our timing model, and are - in a words - "subtracted from the data".

Then we calculate a new set of predicted TOAs, and compare them to the observed again.

After the substraction the periodicity is clearly visible.



It is clearly a sinewave with a 1 year period! And we supposedly corrected for Earth's position and movement. So whats wrong?

Nothing is wrong. Only the pulsar isn't where we think it is. Remember these two formulae?

$$\Delta_{R\odot} = -\frac{1}{c}\vec{r}\cdot\hat{s} = -\frac{1}{c}(\vec{r}_{\rm SSB} + \vec{r}_{\rm EO})\cdot\hat{s}$$

$$\Delta_{S\odot} = -2\sum_i \frac{GM_i}{c^3}\ln\left[\frac{\hat{s}\cdot\vec{r}_i^{\rm E} + r_i^{\rm E}}{\hat{s}\cdot\vec{r}_i^{\rm P} + r_i^{\rm P}}\right]$$

They both include the unit vector from the SSB to the pulsar, which is given by the pulsar sky coordinates.

But if the real pulsar coordinates are slightly different from what we assumed - it caused one year periodicity in our data.

So, we did nothing wrong, just our clock corecctions were unprecise.

We can correct that with the same method we used for the rotational parameters of the pulsar - the least squares fit for the best possible sky coordinates.

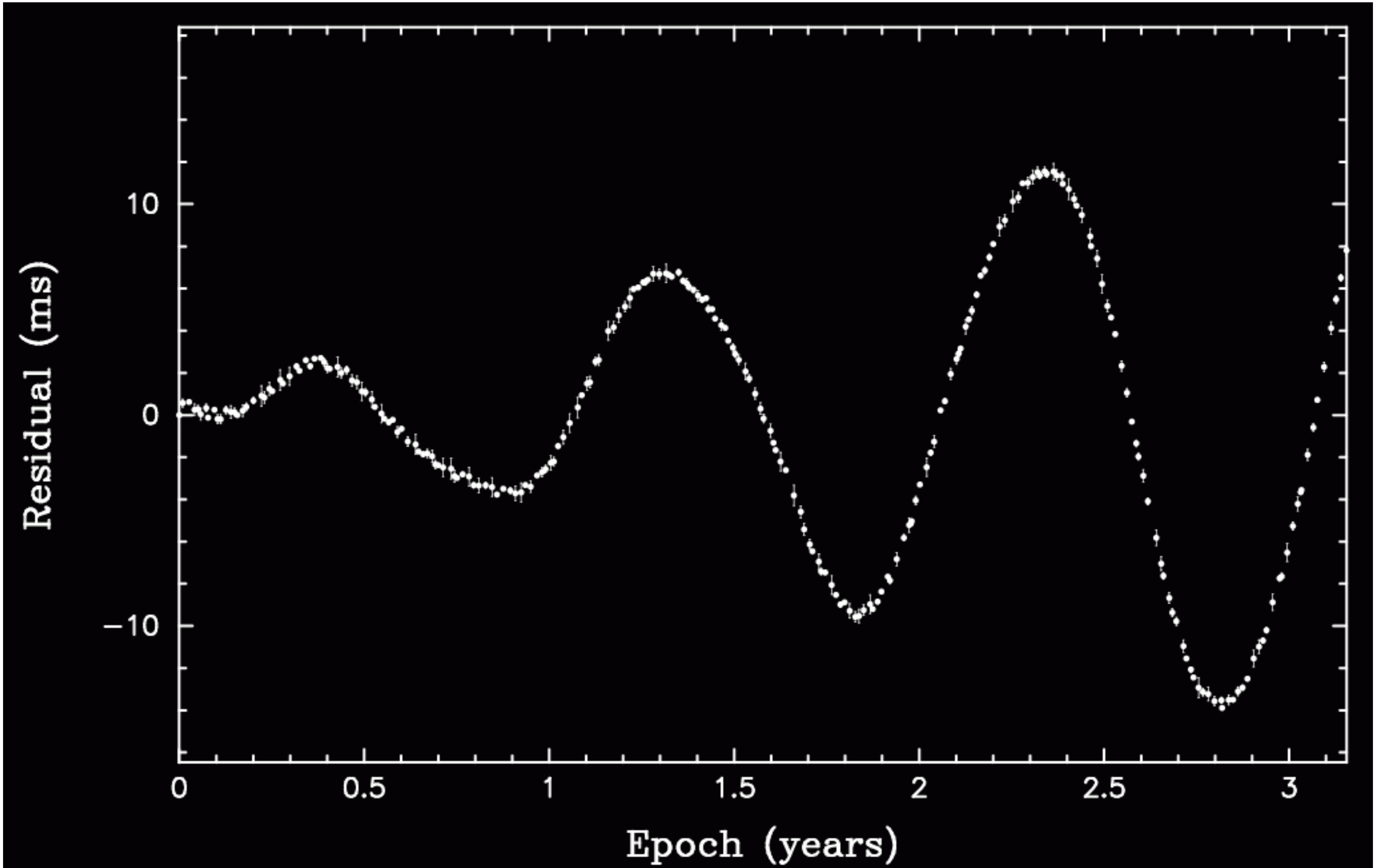
Minimizing the χ^2 again yields the new *s* vector.

Practically we expres it by corrections to the sky coordinates - $\Delta\alpha$ and $\Delta\delta$.

After finding the best values of α and δ (or the coordinates in any other system we may think of) we run the TOA correction/prediction algorithm again.

And again we plot the residuals...

Hmm... What is left is an increasing amplitude sinewave. With a clear 1 year periodicity visible...



What might have cause something like that?

Lets assume, that the pulsar initially was, where we thought it was...

But it started to move away from that position. The effect would be an increasing amplitude sinewave.

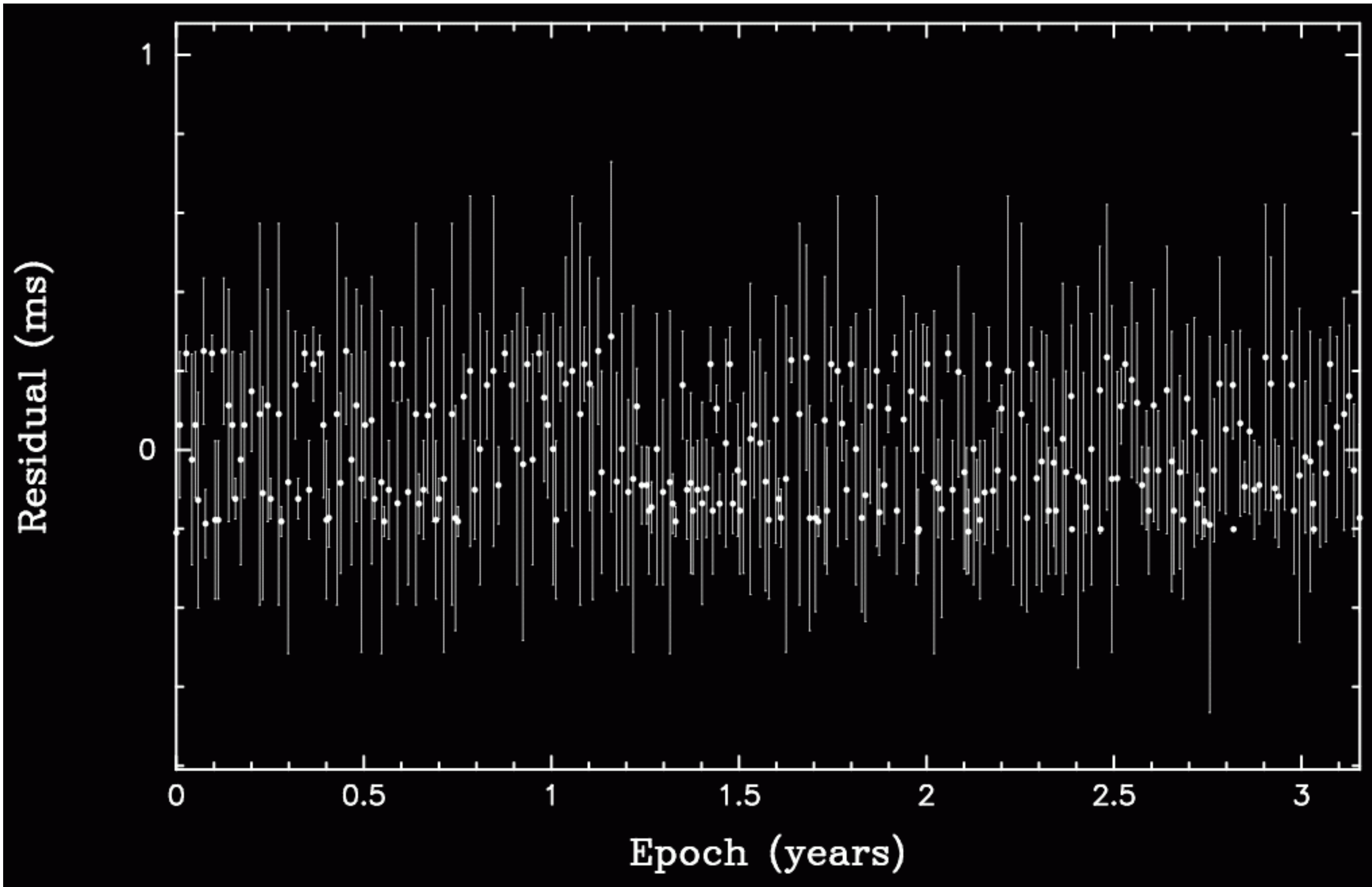
If we express the current pulsar position as:

$$\alpha(t) = \alpha(t_0) + \mu_\alpha (t - t_0),$$
$$\delta(t) = \delta(t_0) + \mu_\delta (t - t_0),$$

and include that in our time correction algorithm, again - by the use of least squares fit - we may find the values of the pulsar proper motion.

Then we include these values in our timing model, and repeat the analysis again.

Finally, this is what you would like to see - nothing but white noise, which is due to the TOA measurement uncertainties comming mainly from the receiver noises (and the pulsar itself, but more on that later) .



If the residuals show only the white noise - this means, that we know everything there is to know about the pulsar (at least from the timing point of view).

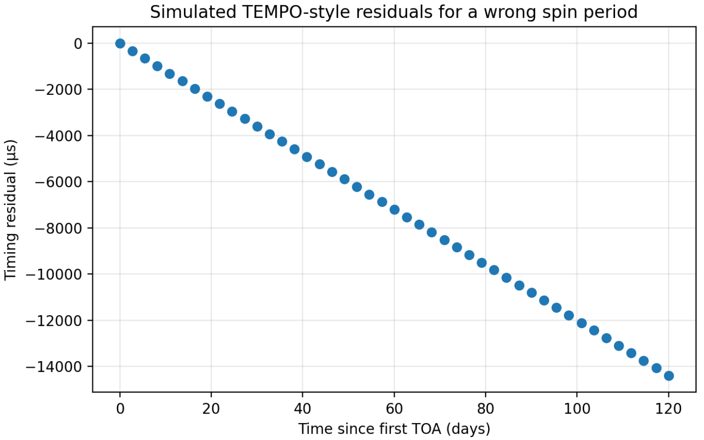
We have a proper timing solution – a set of new (or improved, or corrected) pulsar parameters.

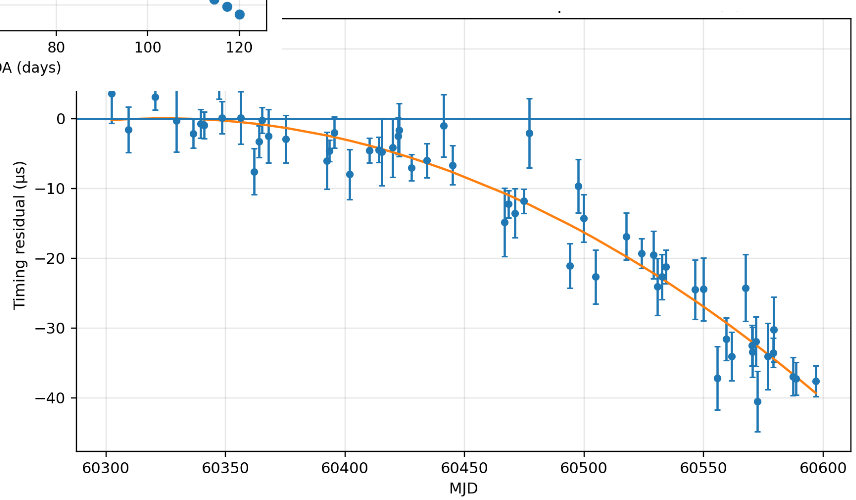
We can calculate P and dP/dt from the parabolic fit.

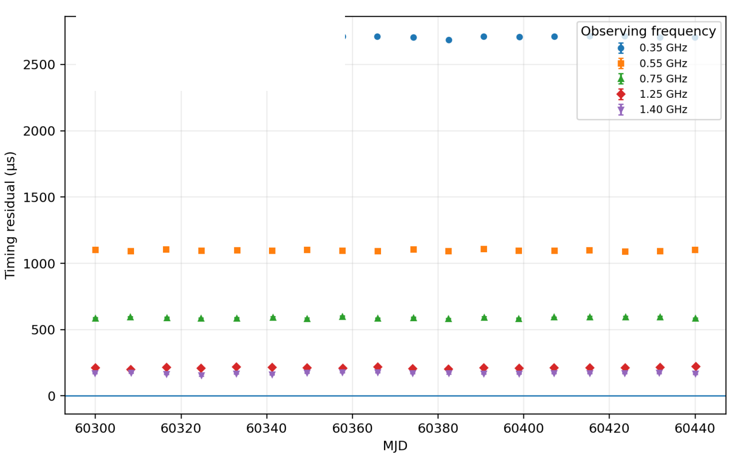
We can derive real sky coordinates from the first sinewave fit.

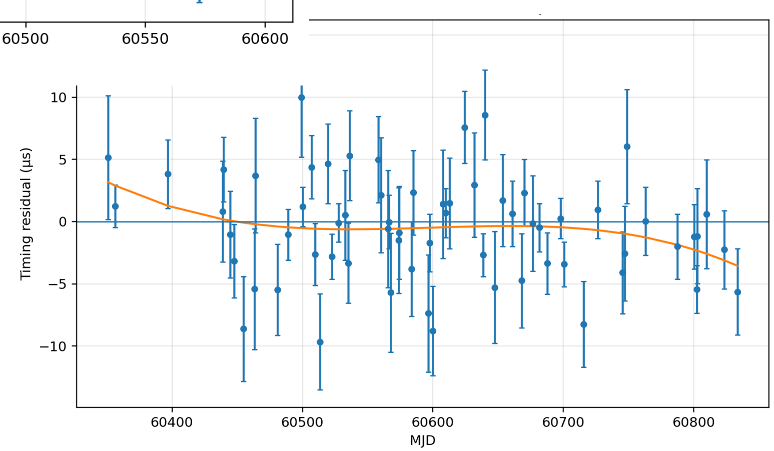
We can obtain pulsar proper motion from the subsequent fit.

What are timing errors for each plot?

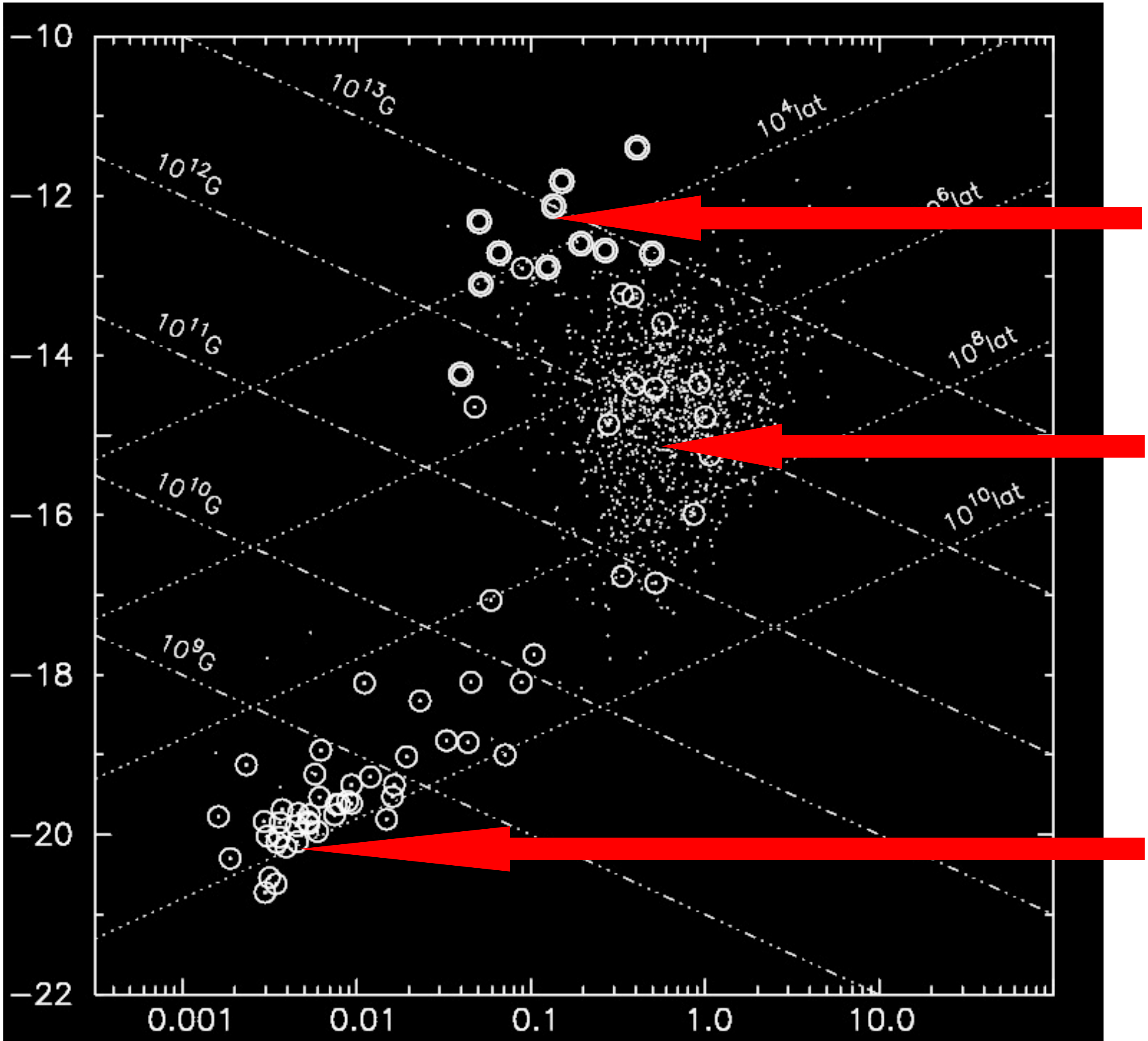








So, what do we know from simple period and slow-down rate measurements?

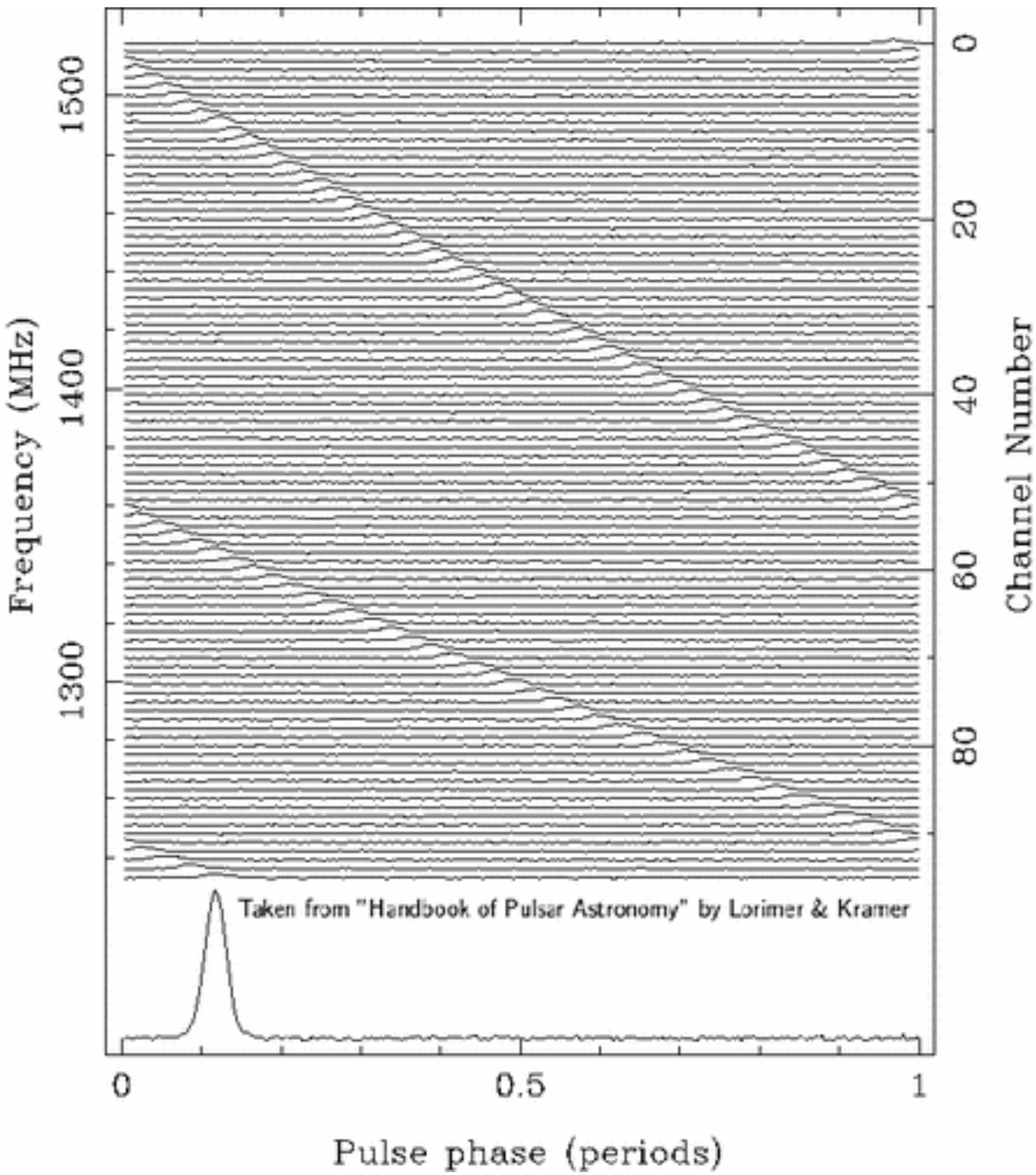


Young pulsars

Regular pulsars

Millisecond (mostly binary) pulsars

Let's just recall the interstellar disspersion effect:



Interstellar medium (in fact the free electrons in it) is a dispersive medium for radio waves.

Radio waves of different frequencies have different speeds, while traveling through such medium.

The efect is such, that the pulse comes at higher frequencies first (the speed of its travel is higher), and at tle lower frequencies later.

How does it help us?

Let's just recall the basic formula for time correction:

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

*ΔD = D * DM*

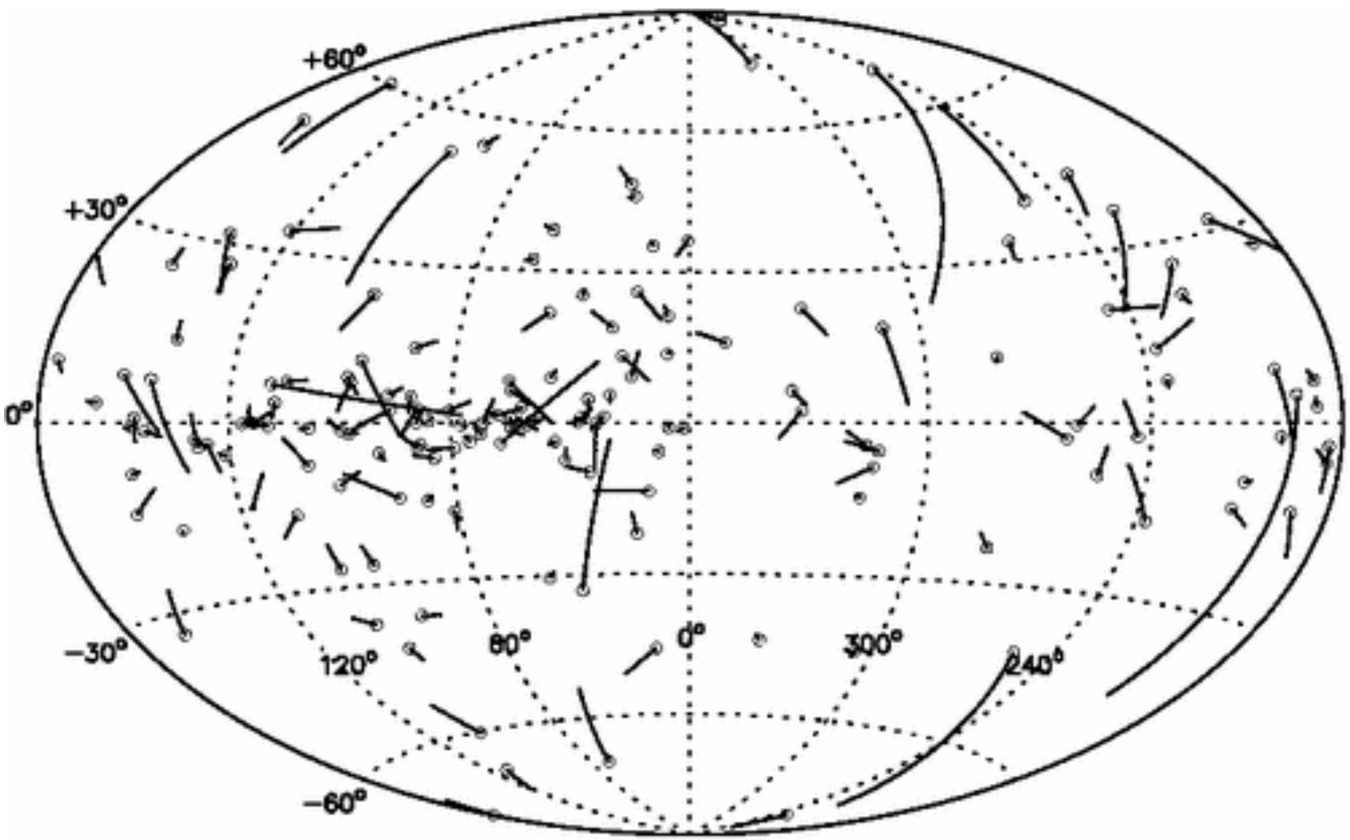
D – disspersion measure constant

DM - the disspersion measure - basically the column density of the free electrons along the line of sight to the pulsar.

f - the observing frequency

If the time correction (and consequently the residuals) depend on the frequency, then we can mesure TOA's on two fifferent frequencies, and compare the residuals...

In many cases we know not only where the pulsars are, but also - how they move:



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

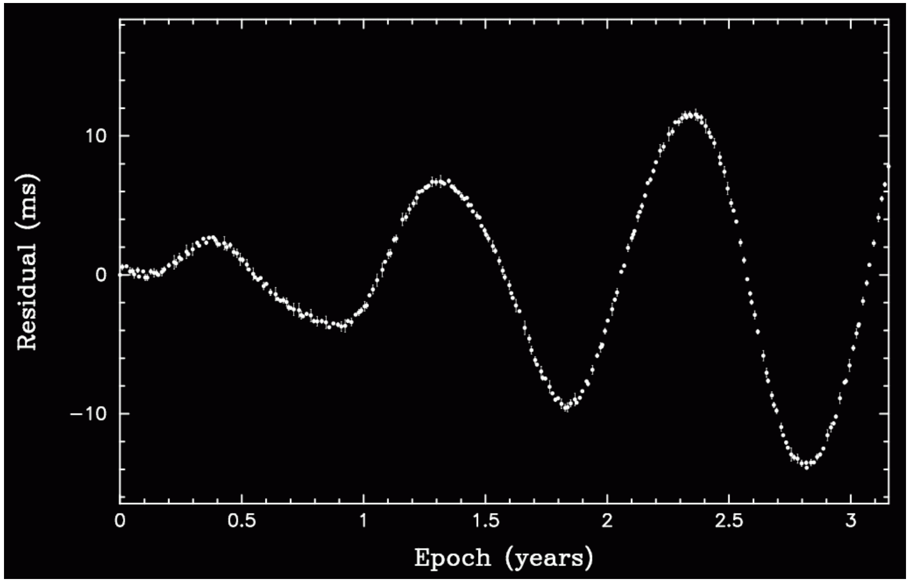
The circles show the current pulsar positions, solid lines represent their movements over the last million years.

We can learn a lot by measuring the pulsar proper motion. Especially, that for some pulsars we can measure the movement as small as a fraction of a *mas/yr* (milli-arc-seconds per year!).

This way we can measure the proper motions for pulsars up to a few kiloparsecs away - which is imposible for regular stars in optical astronomy.

One of the reasons for that is, that the pulsars are very fast objects. Knowing the pulsar proper motion one can easily
calculate its transverse velocity:

$$V_T = 4.74 \text{ km s}^{-1} \left(\frac{\mu_T}{\text{mas yr}^{-1}}\right)\left(\frac{d}{\text{kpc}}\right)$$

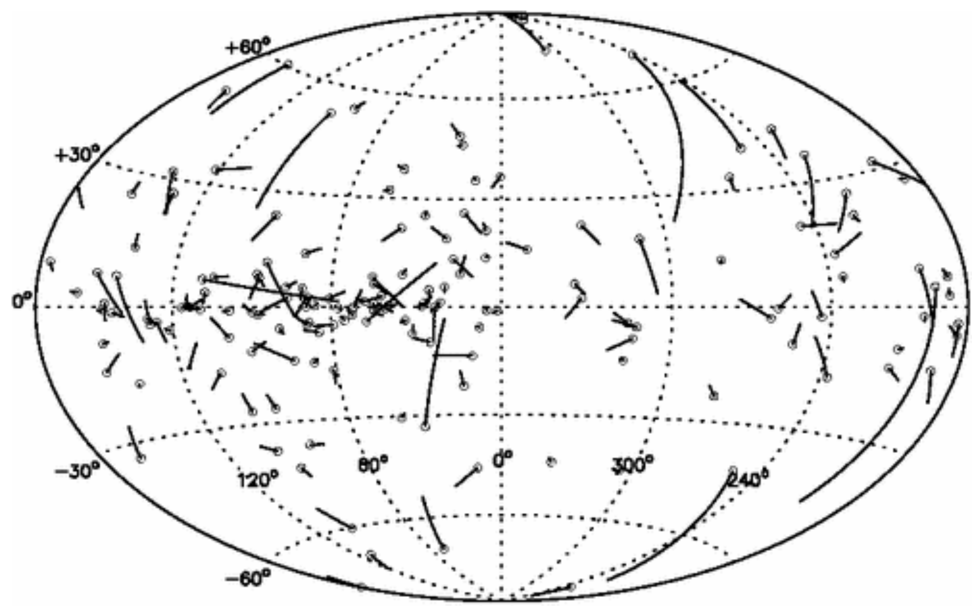


The speeds we get are high indeed. There are pulsars which are moving with up to 1000 km/s. The average speed is close to 70 km/s for regular pulsars and about 120 km/s for binary/millisecond pulsars.

And as one can see - the direction of the movement is completely random.

There are pulsars, that are going away from the Galactic plane, and there are some going towards it - probably going back to where they were born.

What is the reason for such behaviour? No other kind of astronomical objects behaves like this.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

How precisely one can measure pulsar period?

86	J0525-6607	cdp+80	8.0470	2	kkm+03	6.5E-11	5	kkm+03
87	B0525+21	sr68	3.74551267840	3	hlk+04	4.003633E-14	8	hlk+04
88	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	6	[illegible]

Pulsar PSR J0613-0200:

- ✓ Rotation period: 0.00306184403674401 +/- 0.00000000000000005 sec
- ✓ The precission we know it's period allows us to predict the arrival times of all incoming pulses for long (the next 10 million years)!
- ✓ It is the order of magnitude simillar to the best atomic clocks used on Earth!

101	J0611+30	cnst96	1.412090	3	cnst96	*	0	*
102	B0609+37	stwd85	0.29798232657184	18	hlk+04	5.94681E-17	18	hlk+04
103	J0613-0200	lnl+95	0.00306184403674401	5	tsb+99	9.572E-21	5	tsb+99
104	B0611+22	dls72	0.33495996611	16	hlk+04	5.94494E-14	12	hlk+04
105	J0621+1002	cnst96	0.028853860730049	1	sna+02	4.732E-20	2	sna+02
106	B0621-04	mlt+78	1.0390764758510	15	hlk+04	8.30442E-16	12	hlk+04
107	J0625+10	cnst96	0.498397	3	cnst96	*	0	*
108	B0626+24	dth78	0.476622836038	4	hlk+04	1.99573E-15	3	hlk+04
109	B0628-28	lvw69a	1.244418859615	8	hlk+04	7.1229E-15	3	hlk+04
110	J0631+1036	zcwl96	0.287772559545	10	hlk+04	1.046836E-13	3	hlk+04
111	J0633+1746	hh92	0.237093230014	14	hsb+92	1.097495E-14	14	hsb+92
112	J0635+0533	cmn+00	0.033856495	12	cmn+00	*	0	*
113	B0643+80	dbtb82	1.2144405115160	20	hlk+04	3.798787E-15	15	hlk+04
114	B0656+14	mlt+78	0.384891195054	5	hlk+04	5.500309E-14	3	hlk+04
115	B0655+64	dth78	0.19567094516627	16	hlk+04	6.853E-19	12	hlk+04

From ATNF pulsar catalogue:
http://atnf.csiro.au/research/pulsar/psrcat/

Seventeenth significant digit!!!

The fastest pulsar is PSR J1748-2446ad, which is rotating 713 times per second.

Pulsar PSR J0613-0200:

- rotation period: 0.00306184403674401 +/- 0.00000000000000005 seconds
- the precission we know it’s period allows us to predict the arrival times of all incoming pulses for the next 10 million years!
- It is the order of magnitude simillar to the best atomic clocks used on Earth!

The fastest pulsar is PSR J1748-2446ad, which is rotating 713 times per second.

Human ear does not discern individual pulses.

So we can learn a lot by just timing the solitary pulsars:

- their sky coordinates
- their movements
- their age
- their evolutional stage (and of course the overal evolution of a pulsar)
- their magnetic fields
- details of their births (natal kicks)
- their associations with supernova remnants
- their galactic distribution
- the galactic distribution of free electrons (from the dispersion measure)

But that is only a beginning. It gets more interesting with the binary pulsars...